ARTIFICIAL RADIOACTIVITY

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INTRODUCTION

I am speaking tonight on a very new subject, for artificial radioactivity was unknown fourteen months ago. Indeed, some of the facts I shall speak about were brought to light within this very month. From the standpoint of physics, the developments within the year have gone forward with almost incredible rapidity, with results that have profoundly modified and enlarged our understanding of the atom.

HISTORICAL BACKGROUND

For a historical background, however, we must go back to 1896, the year of Roentgen's discovery of x-rays. At that time Professor Henri Becquerel investigated the possibility that this mysterious radiation might be given off spontaneously from natural substances. He had in mind particularly the class of substances that give off light of their own accord—phosphorescent substances. Becquerel had been studying the properties of phosphorescent substances and happened to have in his possession at that time some phosphorescent salts of uranium, which he had prepared fifteen years before. Almost immediately he discovered that uranium salts do give off a radiation like x-rays; for when the uranium salts were placed near a photographic plate enclosed in a light-tight box, after a period of time the photographic plate was activated.

Very soon Rutherford, then at McGill, showed that the radiations continuously emanating from uranium could be divided into two types: one called the alpha rays, which were very easily absorbed in matter and produced intense ionization, and a much more penetrating type called the beta rays. When a still more penetrating type of radiation was discovered, Villard named them the gamma rays. These names for the three types are still used, although now it is known that the alpha rays are the nuclei or centers of helium atoms, the beta rays are high-speed electrons, and the gamma rays are indeed very penetrating x-rays, which are of the same nature as light.

Soon other radioactive substances were discovered, and in 1898 Madame Curie isolated radium. At this stage a number of radioactive substances had been found. Some appeared to give off radiation continuously and constantly, while the radiation from others decreased with time.

This complicated mass of facts was reduced to order by the transformation theory of Rutherford and Soddy in 1903. According to this theory, the atoms of the radio-elements, unlike the atoms of the ordinary elements, are not stable, but undergo spontaneous disintegration, accompanied by the expulsion of an alpha or a beta particle. After the disintegration, the resulting atom has physical and chemical properties entirely different from the parent atom. It may in turn be unstable and pass through a succession of transformations, each of which is characterized by the emission of an alpha or beta particle.

These processes may be illustrated by considering the changes in radium, shown schematically in the first slide (Fig. 1). At any moment an atom of atomic mass 226 may become unstable and break up with explosive violence, expelling an alpha particle with a characteristic speed. Since the alpha particle is a helium atom of mass 4, the resulting atom is lighter than before and becomes an atom of a new substance, radon, of mass 222, which is an inert radioactive gas. This in turn breaks up, with the liberation of an alpha particle, and is converted into an atom of a nongaseous element, radium A. The next element in the series, radium B, emits a beta particle and thereby transforms into radium C, which is an element of very nearly the same weight and one unit up the periodic table.

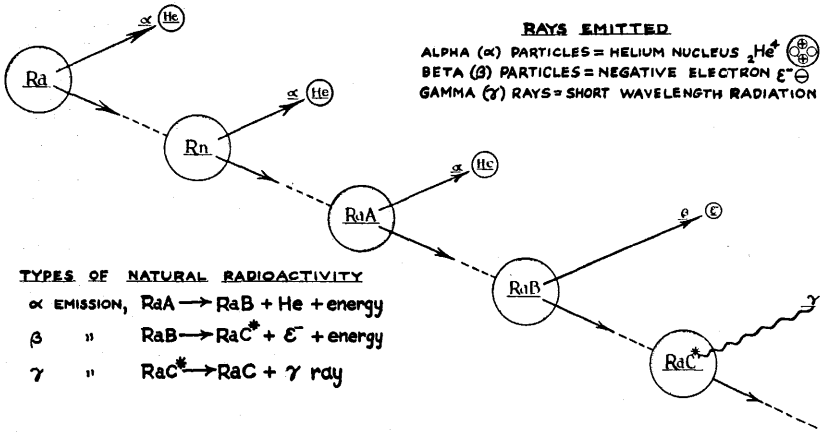
For the purposes of the evening, this is all I need to say about the natural radioactive substances, the unstable atomic species existing at the present time in nature.

We now turn our attention to 1919, when Lord Rutherford for the first time transformed the ordinarily stable element nitrogen into oxygen. By this time Rutherford's theory of the atomic nucleus was well established. It was generally accepted that the nucleus, or center, of the atom contains more than 99.9 per cent of the atom's mass and energy and, moreover, that the nucleus possesses a positive charge that determines the number and configuration of the electrons outside the nucleus, and these extra-nuclear electrons determine the atom's

NATURAL RADIOACTIVITY
NATURAL SPONTANEOUS DISINTEGRATION

DISCOVERED IN URANIUM BY BECQUEREL (1896). RADIUM ISOLATED BY MME. CURIE (1898). RADIATIONS WITH DIFFERENT PENETRATING POWERS OBSERVED, CALLED α, β, AND γ RAYS. TRANSFORMATION THEORY ADVANCED BY RUTHERFORD AND SODDY (1903)—ATOMS OF RADIO-ELEMENTS ARE UNSTABLE AND UNDERGO SPONTANEOUS DISINTEGRATION.

EXAMPLE — SUCCESSION OF TRANSFORMATIONS (DECAY) OF RADIUM



· TRANSMUTATION ·
ARTIFICIALLY PRODUCED DISINTEGRATION

RUTHERFORD (1919) BOMBARDED NITROGEN WITH NATURAL ALPHA PARTICLES

reaction equation $_2He^4 + {}_7N^{14} \longrightarrow {}_8O^{17} + {}_1H^1 + \text{energy}$

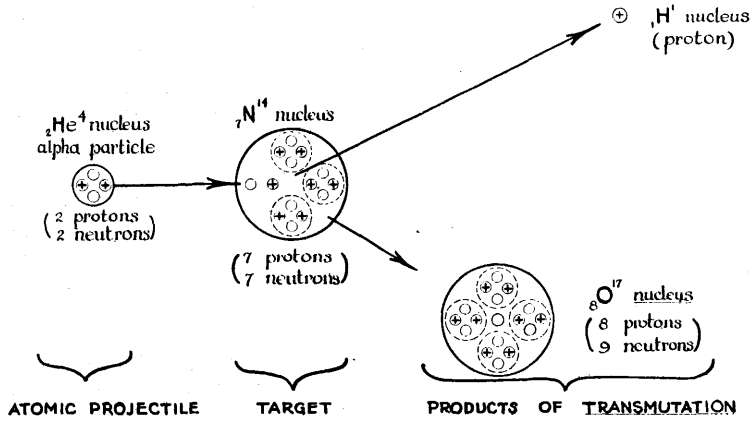


FIGURE 1—Upper. FIGURE 2—Lower.

place in the periodic table. Thus, on this theory, the age-old problem of alchemy, the conversion of one chemical element into another, was reduced to the definite problem of changing the amount of positive electricity in the atomic nucleus.

This Rutherford succeeded in doing by bombarding nitrogen with the alpha particles from radium. Several lines of evidence indicated that the constituent particles of the nucleus (then thought to be protons and electrons) were closely and tightly bound together, and that, therefore, disrupting the nucleus could be accomplished only by bombardment with atomic projectiles of very high energy, such as the alpha particles from radium. I should like to spend some time describing Rutherford's great experiments, for his works are classics in experimental physics, but time permits me only to state the established experimental results. He showed that when an alpha particle or helium nucleus, traveling at high speed, hits the nucleus of a nitrogen atom, occasionally the alpha particle sticks, and at the same time a proton, or hydrogen nucleus, is thrown off with a great deal of kinetic energy. Thus is formed O^{17}, a heavy form of oxygen which was not known in nature at that time but since has been discovered as a normal constituent of chemical oxygen by Giauque and Johnston—and by the way, the latter gentleman is Professor Johnston of your department of chemistry.

This classic nuclear reaction is shown in the next slide (Fig. 2). For most purposes, an atomic nucleus is sufficiently specified by giving the atomic number, which is the positive charge on the nucleus in integral multiples of the proton charge, that determines its place in the table of elements—what element it is—and the mass number, in multiples of the proton as well. Actually, in fact, atomic nuclei do not have masses that are exact multiples of that of the proton, but that need not worry us here. Thus the upper right-hand corner of the symbol of the element is reserved for the isotopic mass, and the lower left-hand corner for the atomic number, and the nuclear reaction of Rutherford is written as shown in the slide. The double charge on the helium nucleus is added to the seven-fold charge of the nitrogen, and the single charge of the hydrogen is subtracted, resulting in a net increase of one positive charge, thereby forming oxygen. Likewise, the net increase in weight is 3 units, making O^{17}.

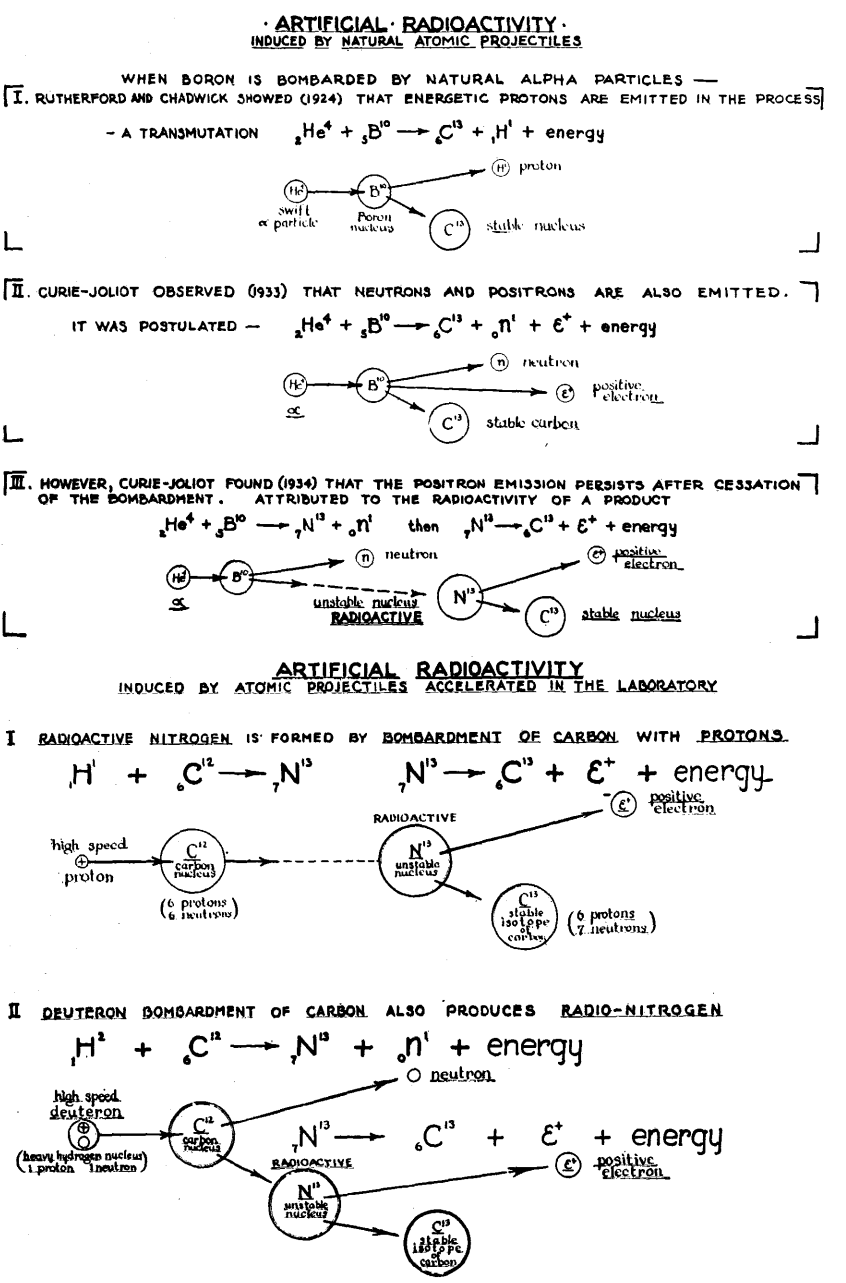


FIGURE 3—Upper. FIGURE 4—Lower.

Following the first definite example of the artificial transmutation of the elements, many other transmutations were carried out. Most of the lighter elements up to potassium were transformed, one into another, by alpha particle bombardment, in each case with the emission of a proton.

The next episode in our historical background brings us up to 1932, when Irene Curie, the daughter of Madame Curie, and her husband, F. Joliot, discovered that boron gives off positrons, the positive electrons discovered that same year by Professor Carl Anderson of the California Institute of Technology, and neutrons, the neutral particles of protonic mass discovered by Chadwick only a few months earlier. They concluded that the reactions depicted on the next slide (Fig. 3) occurred. When boron is disintegrated by alpha particle bombardment, alternative reactions may occur: either a proton may be emitted, as observed by Rutherford and Chadwick, or a neutron and positive electron together—as though a proton is not itself a simple particle but is made of a neutron and positive electron, and that sometimes the process of expulsion of the proton in the reaction is so violent that the proton itself is broken up into its constituent parts.

THE DISCOVERY OF ARTIFICIAL RADIOACTIVITY

The next episode is the birth of artificial radioactivity. One day, more than six months after they had first noticed the emission of positrons from boron bombarded by alpha particles, Curie and Joliot observed (accidentally, I believe) that the positron emission continued on after the alpha particle bombardment had been stopped—they happened to remove the radium from the vicinity of the boron. With this observation, they had discovered that a new kind of radioactivity is stimulated in boron by alpha particle bombardment. This discovery made it evident that the neutron and positron do not come off simultaneously when boron is bombarded by the alpha particle, but that the neutron in the reaction is emitted first, leaving a nucleus having a charge of 7 (hence, the nitrogen nucleus) and a weight of 13, which is lighter than ordinary nitrogen and presumably, therefore, unstable. They proved chemically that the radioactive substance formed is, in fact, an isotope of nitrogen, and christened it "radio-nitrogen." As shown in the slide, the positron emission converts the radio-nitrogen into C^{13}.

In those pioneer experiments they produced two other new radioactive substances—radio-magnesium and radio-silicon—and since that time other radio-substances from alpha particle bombardment have been discovered by various investigators.

In their first discussion of their important discovery, Curie and Joliot suggested that such radioactive substances might well be produced by bombardment with other atomic projectiles, especially protons, deuterons, and neutrons. This suggestion seemed to be almost a certainty to us in Berkeley. Since, for more than a year, we had been studying the disintegration of various elements under deuteron bombardment, and had observed the almost universal emission of protons and neutrons from bombarded targets, it appeared most plausible that the neutrons we had been observing so universally were involved in the alternative nuclear reaction in which artificial radioactive substances were formed.

In particular, it seemed likely that radio-nitrogen could be formed by a deuteron entering a C^{12} nucleus, forming N^{13}, with the emission of a neutron, or by the direct addition of a proton to the C^{12} nucleus, as shown in the next slide (Fig. 4). My colleagues, Dr. M. C. Henderson and Dr. M. S. Livingston, and I investigated this interesting possibility, and immediately we found that radio-nitrogen is formed, indeed, in both of these ways. In those first experiments we also bombarded various other substances with high-speed deuterons, and found, to our surprise and joy, evidence of the production of many new radioactive substances in addition to radio-nitrogen. At about the same time several other laboratories in the world, notably Cambridge, Washington, and Pasadena, more or less independently carried on investigations establishing that radioactive substances can be produced in this way.

In the intervening months, intensive work in the various laboratories has gone forward, with the result that a great many new radioactive substances have been produced, identified, and studied more or less extensively. Also, following the discovery of Professor Fermi, many new radioactive substances produced by neutron bombardments have been studied. Although the discovery of artificial radioactivity is hardly more than a year old, the facts that have been brought to light are already so extensive that I could hardly hope to give an adequate summary this evening. It therefore would seem desirable that I confine my attention for the remainder of the

time to some of the results of recent investigations carried on by my colleagues and myself in California.

EXPERIMENTAL METHODS

But before discussing experimental results, it is desirable to say something about experimental methods for accelerating protons and deuterons to high speeds. There is a natural tendency to relegate to the background the experimental methods and techniques and to regard the results brought to light in nuclear investigations as of first importance. It is so easy to forget that the nuclear investigations are made possible by the development of experimental methods and techniques. How greatly was nuclear physics enriched by the cloud chamber of C. T. R. Wilson!

Methods for the acceleration of charged particles can conveniently be classified into three types: First, the high-voltage method, in which the ions fall through a requisite difference of potential in a vacuum tube. The second method might be called the surf-board method, because the ions are caused to travel along in the field of a traveling wave. The third class of methods of accelerating ions might be termed "resonance methods," or methods of multiple acceleration.

The high-voltage method is, in a sense, the most straightforward, and has much to commend it and is widely used. In the classic experiments of Cockcroft and Walton, in which, for the first time, transmutations were accomplished by bombardment with accelerated ions, a vacuum tube capable of withstanding about 800,000 volts was used. Lauritsen and his collaborators in Pasadena have accomplished a great deal with a vacuum tube, across which is applied about a million volts supplied by the high-voltage transformers in the high-tension laboratory of the California Institute of Technology. Using a Van de Graaff generator, Tuve, Hafstad, and Dahl, in Washington, have been able to accelerate ions at voltages as high as 1.2 million. This high voltage was distributed along a long vaccum tube very nicely, by means of a series of electrodes maintained at proper differences of potential by the corona along the tube. Van de Graaff and his collaborators at Round Hill, Massachusetts, are constructing a similar type of tube in which the voltage is distributed between the electrodes by a series of resistances. The tube is ultimately intended to withstand the full voltage available from their gigantic electrostatic generator, which is more than five million.

Professor J. W. Beams, at the University of Virginia, during the past year or two has been engaged in the development of the surf-board method, and already has made such progress that it appears that the method will be very useful for producing small currents at very high voltage. Beams has already succeeded in accelerating protons to voltages above two million, and it appears not improbable that he will be able to reach double this voltage in this way. The inherent features of the method are such as to restrict it to the production of small current in pulses, a restriction which, however, makes it almost ideally adapted to cloud chamber experiments.

The methods of multiple acceleration by resonance with an oscillating electric field have the advantage that they do not require high voltages. The general resonance principle is familiar even to the layman. A child in a swing knows that a high swinging velocity can be achieved by one big push, corresponding to the single acceleration of an ion by application of high voltage, or by a succession of small pushes properly timed with the swinging motion, corresponding to the resonance acceleration of ions. One type of apparatus that uses this resonance principle involves both a magnetic field and an oscillating electric field. We have in our laboratory two of this sort. The larger one of the two, which has been used in the nuclear investigations that I shall speak about, is shown on the next slide (Fig. 5). The most prominent feature of the apparatus is the giant electro-magnet, weighing something like 85 tons. Thus far we have accelerated deuterons to energies only slightly above five million, and the most energetic deuterons we have actually used in nuclear investigations had energies of about 4.5 million volts. The time, of course, will come when we will want to go up to higher voltages, and from our recent experience we are confident that, by using the full power of the magnet, we will be able to produce deuterons of energies above ten million volts, and possibly above fifteen million volts.

The ions are accelerated in the vacuum chamber between the poles of the magnet. The function of the magnetic field is to cause the ions to travel with constant angular velocity most of the time in circular paths. Within the chamber there are two semicircular hollow electrodes, between which is applied a high frequency potential difference. The ions circulate

FIGURE 5

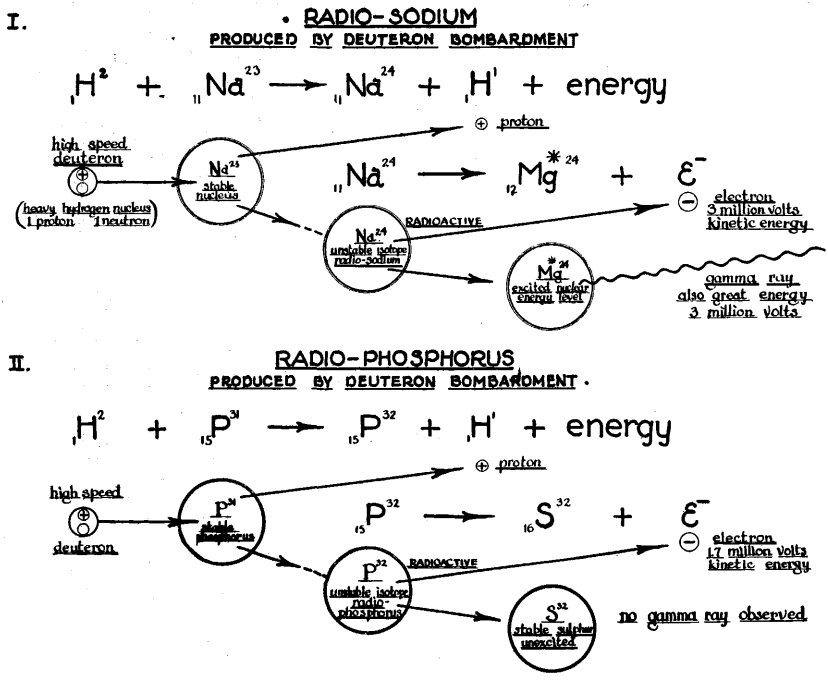

I.
RADIO-SODIUM
PRODUCED BY DEUTERON BOMBARDMENT
$_1H^2 + {}_{11}Na^{23} \rightarrow {}_{11}Na^{24} + {}_1H^1 + \text{energy}$
high speed deuteron
(heavy hydrogen nucleus 1 proton 1 neutron)
stable nucleus
proton
$_{11}Na^{24} \rightarrow {}_{12}Mg^{*24} + \varepsilon^-$
electron 3 million volts kinetic energy
RADIOACTIVE
unstable isotope radio-sodium
excited nuclear energy level
gamma ray also great energy 3 million volts
II.
RADIO-PHOSPHORUS
PRODUCED BY DEUTERON BOMBARDMENT.
$_1H^2 + {}_{15}P^{31} \rightarrow {}_{15}P^{32} + {}_1H^1 + \text{energy}$
high speed deuteron
stable phosphorus
proton
$_{15}P^{32} \rightarrow {}_{16}S^{32} + \varepsilon^-$
electron 1.7 million volts kinetic energy
RADIOACTIVE
unstable isotope radio-phosphorus
stable sulphur unexcited
no gamma ray observed

FIGURE 6

around from within one electrode to within another, and as they cross the diametrical region they gain increments of kinetic energy corresponding to the potential difference. Inasmuch as the angular velocity of the ions is determined by the magnetic field alone, they can be made to spiral around in synchronism with the oscillating electric field, with the result that they can be made to gain successive increments of velocity, and hence, going faster and faster on ever widening spirals, finally they emerge at the periphery of the apparatus where they are withdrawn by a deflecting electrostatic field through a thin aluminum window to the outside world. The swiftly moving deuterons travel a distance of about 17 cm before being stopped by their loss of energy in passing through air. The beam is visible as a bright blue glow; for the beam passing through the air excites the atoms and molecules to the emission of visible light. Experiments on the radioactivity induced by deuteron bombardment are carried out simply by placing the substance to be bombarded in the path of the deuteron beam just outside the aluminum window for any desired period of time, and then, taking the bombarded target away to an ionization chamber or a Wilson cloud expansion chamber, or any other apparatus used for studying the radiation given off from the activated target.

THE NEUTRON-CAPTURE REACTION

I have already remarked that in our first experiment, in which we bombarded various substances with deuterons, there was evidence of the formation of several new radioactive substances. In some cases, radioactive nuclei are formed in nuclear reactions, in which neutrons or alpha particles are emitted. But in the majority of cases it is found that the neutron of the deuteron is captured and the proton is emitted with high speed. This general type of reaction, which, for convenience, is called the neutron-capture reaction, has been observed to occur for many of the elements, and is conveniently illustrated by the cases of radio-sodium and radio-phosphorus shown in the next slide (Fig. 6).

Thus Na^{23}, upon being bombarded by the deuterons, acquires the neutron of the deuteron and becomes heavier by the weight of the neutron; that is Na^{24}. Na^{24} does not occur in nature and is energetically unstable, and in the course of $15\frac{1}{2}$ hours, on the average, the radio-sodium atom emits a high-speed electron

(i. e., a beta particle) from its nucleus, becoming Mg^{24}. The newly created magnesium nucleus is formed with an excess of energy, which it immediately radiates as a very energetic gamma ray of energy above three million volts. The beta and gamma rays emitted from radio-sodium are thus more powerful than the radiations from radium. Indeed the gamma rays are more powerful than those from any of the known natural radioactive substances.

In a like manner, radio-phosphorus is formed. Radio-phosphorus is interesting in two respects. In the first place, it has the longest average lifetime of any of the artificial radioactive substances thus far studied. Its half-life is about 15 days. The other interesting feature of radio-phosphorus is that it does not emit any gamma rays. A pure beta ray spectrum is observed. It appears that the S^{32} nucleus, that results when P^{32} emits a beta particle, is formed in its normal state without an excess of energy to be radiated.

THE TRANSMUTATION FUNCTION FOR THE NEUTRON-CAPTURE REACTION

Perhaps the most interesting result of all was the mere fact that we were able to transform elements of as high atomic number as sodium and phosphorus by bombardment with deuterons of less than two million volts of energy. It was quite incomprehensible that deuterons of such low energy were able to overcome the high repulsive forces of the positive charges on these nuclei, for it was presumably well known that these repulsive forces produce an effective barrier around the nuclei corresponding to several million volts.

Prior to the advent of the wave mechanics, it was thought that a charged particle bombarding a nuclear potential barrier does not penetrate into the nucleus unless it has enough energy to climb the nuclear wall and enter over the top, and so, in accordance with classical ideas, one would not expect sodium to be transformed by bombardment with two million volt deuterons. But Gurney and Condon, and Gamow, independently applied the wave mechanics to nuclear problems and made it clear that charged particles penetrate right through nuclear potential barriers. Indeed it was the existence of this tunnel effect that encouraged Cockcroft and Walton to try to disintegrate lithium by bombardment with protons of less than a million volts energy, with the result that is now so well known.

But even the Gamow theory did not make plausible the observation of the transformation of sodium by one and one-half million volt deuterons. The apparent incompatibility of the experiments with current theory was enhanced by the further observation that copper could be rendered radioactive by bombardment with deuterons of slightly more than two million volt energies.[1] Thus it was of much interest to my colleagues, Drs. R. L. Thornton and E. M. McMillan, and myself, to investigate the variation of the nuclear reaction with the energy of the bombarding deuterons in the several cases, which we did as follows:

In order to obtain an energy-yield curve for a reaction giving a radioactive product, one measures the intensity of activation of a number of samples exposed to bombardment by particles of different energies. The relative bombarding current and exposure time must be accurately known for each sample, a requirement which is most easily and satisfactorily met by activating them simultaneously. This was done by using as a target a stack of thin foils of the substance being investigated, through which the activating deuteron beam was sent. The energy of the deuterons traversing any particular foil is then determined by their initial energy, and the stopping power of the preceding foil and the measured activities give directly the differential excitation curve. Thus, for example, a stack of 15 aluminum foils, each having a stopping power of about 8 mm. air equivalent, was placed in the beam of the deuterons emerging from the aluminum window of the magnetic resonance accelerator, and, after exposure to the beam for a few minutes, was removed, and the radioactivity induced in each foil was observed by placing the individual foils in the ionization chamber of an electroscope.

The variation of the probability of activation of an aluminum nucleus with the energy of a bombarding deuteron (sometimes called the differential excitation function, or thin target transmutation function) thus observed, is shown in the next slide (Fig. 7). I am showing the aluminum results first because it it believed in this case the observations were most

[1]Recently we have made preliminary observations that indicate that radio-molybdenum is formed by bombardment of molybdenum with 3.5 million volt deuterons, and that possible gold is rendered radioactive by bombardment with 4.5 million volt deuterons. However, further work must be carried out before it can be concluded with confidence that these deuteron reactions actually occur, as there are yet possibilities of contaminations.

precise. For similar observations on radio-sodium and radio-silicon, thin mica foil was used, as mica contains both silicon and sodium. Since the half-life of radio-silicon is 2.8 hours, and that of radio-sodium is about 15.5 hours, the two radio-activities were readily distinguished in the mica foil, the silicon activity being predominant in the first few hours after deuteron bombardment, and the sodium activity persisting for days afterwards. The results in these two cases are shown in the next two slides (Figs. 8 and 9). The observations with copper foils are shown in the last slide (Fig. 10).

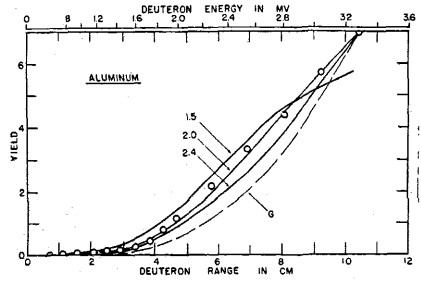


FIGURE 7—Upper left.

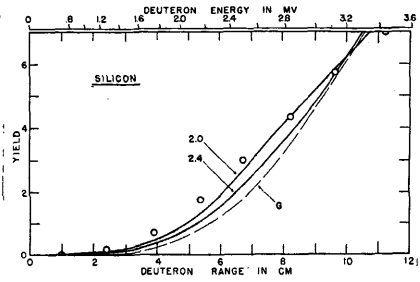


FIGURE 8—Upper right.

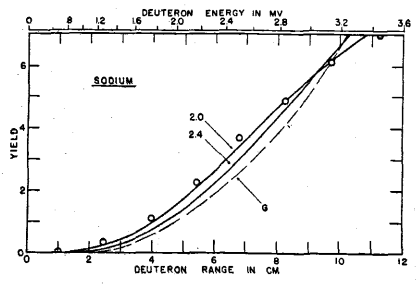


FIGURE 9—Lower left.

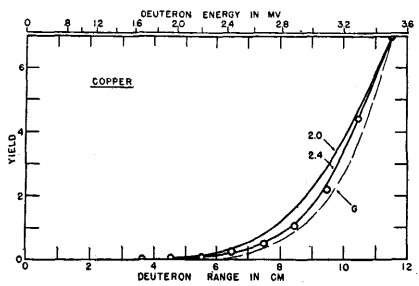


FIGURE 10—Lower right.

It is evident that the excitation curves in the four cases are of similar form. The yield of radioactive substance for a thin target, plotted against the range of the bombarding deuteron, instead of its energy, rises approximately linearly with the range (with a "tail" at the beginning). The experimental results clearly indicated a new general kind of excitation function for this class of nuclear reactions.

THE OPPEMHEIMER-PHILLIPS THEORY

We were all curious to know something about the fundamental physics underlying this new type of transmutation

function, and Professor J. R. Oppenheimer and Dr. Melba Phillips soon came forward with a theory that explained everything in most gratifying fashion. The essence of their theoretical explanation lies in the fact that reactions of the type here concerned can occur without requiring the penetration of a charged particle through the nuclear coulomb potential barrier which opposes the entry of the deuteron. The mechanism postulated can be described in the following way: Consider the deuteron as built of a proton and neutron with the binding energy I. Because of the wave nature of the particles, this structure is not confined within a sharply limited volume, but there is a finite chance that the neutron or proton may be found some distance away from the center of mass. This chance decreases rapidly with the distance. When the deuteron is projected against the nucleus, the proton is held back by the coulomb field. This distorts the probability distribution of the proton in such a way that, for a given distance of the deuteron center of mass from the nucleus, the chance of finding it in the center of the nucleus is very much reduced. On the other hand, the neutron is immune to the action of the electrostatic field, and its probability distribution can overlap the center of the nucleus; this distribution is, in fact, distorted by the forces involved in the deceleration of the neutron in such a way as to increase its density on the side toward the nucleus. Therefore the neutron has a relatively larger chance of being within the nucleus, and while there, of undergoing a reaction in which it becomes bound, forming a new nucleus. The extension of the neutron distribution varies with I, becoming greater as I decreases. It is the relatively small value of I (about 2 million volts) that causes the slow energy variation of this type of reaction by flattening out the neutron probability distribution.

The actual shape of the curves giving the variation of the neutron-penetration with energy depends on the value of I. Since this most probably lies between 2 and 2.4 million volts, as indicated by other experimental evidence, the curves for these two cases have been compared with the experimental values. They are plotted as solid lines, as shown in the several slides. The ordinates of the theoretical curves are adjusted to make them fit at the highest experimental point, except in the cases of sodium and silicon, where the measured values of these are almost certainly too low because of recoil effects.

The Gamow function is also plotted on the figures as dotted lines for comparison. It is seen that the results are in gross disagreement with the Gamow theory, but on the other hand, the results of Oppenheimer and Phillips show a very satisfactory agreement with the observed values. Consider the first case of aluminum, which is the most trustworthy experimentally. With pure aluminum foils the activity if very large compared to that of any possible contamination. There is no error in the highest point caused by recoil. It is seen that the Oppenheimer-Phillips function with I = 2.0 fits extremely well, while with I = 1.5 and I = 2.4 it is off by more than the experimental error.

The fit for sodium and silicon is also best for I = 2.0. Here the possibility of experimental error is somewhat greater, and the apparent deviation in the case of silicon between 1.5 and 2.5 million volts may not be real. The results for these two elements are of chief interest in showing that this type of excitation curve is not a characteristic of any particular reaction, but of a class of reactions. The comparative values for sodium and silicon show also that the steepness of the curve increases with atomic number, as it should.

For copper the fit seems to be best with I = 2.4. Here, because the greatest variation of the function occurs in a narrower voltage range, the different theoretical curves are not as widely separated as in the other cases, and the apparent better agreement with I = 2.4 may not be real.

Thus the theory of Oppenheimer and Phillips, which was developed from such attractively simple and reasonable assumptions, is adequate to explain the observed excitation curves. The agreement of the experiment with the theory is so satisfactory in detail that the results yield a completely independent measure of the binding energy of the deuteron, and this result itself is of much importance.

Moreover, acceptance of the Oppenheimer-Phillips theory as correct leads to another very important conclusion. Just as the variation of the transmutation yield with energy for a given atomic number is slower than expected on the Gamow theory, likewise the variation with atomic number for a given energy is much slower. This has the consequence that it will be possible, with the available deuteron energies, to produce nuclear reactions much farther up the periodic table than one could have hoped for before.

UTILITY OF ARTIFICIAL RADIOACTIVITY

Before closing it is well to remark that, now that radioactive forms of many of the elements can be manufactured in the laboratory, many new avenues of research are opened up. It is reasonable to expect that artificial radioactive substances will play a possibly more important role in the physical and biological sciences in the not distant future than the natural radioactive substances have in the past. Certainly extensive study of the artificial radioactive substances will lead to a greatly enlarged understanding of atomic structure. But, more particularly, these new radioactive substances provide many and varied ideal sources of beta and gamma rays. For example, radio-phosphorus provides beta radiation, free from gamma rays, that can be used conveniently for studies of the behavior of high-speed electrons in matter. Also some of the new radioactive substances give off gamma rays that are far more energetic and penetrating than any from the natural radioactive substances, and the use of these gamma ray sources undoubtedly will lead to important advances in our knowledge of the interaction of radiation and matter.

There may result also many important biological applications. I hesitate to express views in this direction, but some of my medical colleagues think it quite possible that the discovery of artificial radioactivity will ultimately be of great importance to medicine. Opinions of this sort, of course, are highly speculative, and I leave it to you to estimate the advantages for radiation therapy and biological research, of radioactive substances having practically any desired chemical and physical properties.

In conclusion, may I say that, while I have not given you a comprehensive survey of this new world of knowledge and investigation, I do hope that I have given enough of an account of things that have interested us in California in recent months, to make it clear that there is a new science—shall we call it nuclear physics or shall we call it nuclear chemistry?